

AD-A147 660

CORRELATION OF ELECTRONIC CHARGE TRANSFER TRANSITIONS  
AND ELECTROCHEMICAL (U) YORK UNIV DOWNSVIEW (ONTARIO)  
DEPT OF CHEMISTRY E S DODSWORTH ET AL. OCT 84 TR-33  
N00014-78-C-0592

1/1

UNCLASSIFIED

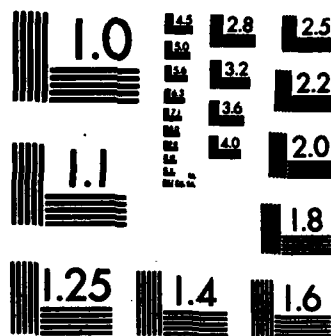
F/G 7/4

NL

END

FILMED

4711



MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A147 660

OFFICE OF NAVAL RESEARCH

Contract N00014-78-C-0592

Task No. NR 051-693

TECHNICAL REPORT NO. 33

Correlation of Electronic Charge Transfer Transitions and Electrochemical Potentials. The Bipyrzine(Tetracarbonyl)Molybdenum(O) System in Various Solvents

BY

Elaine S. Dodsworth and A.B.P. Lever\*

Prepared for Publication

in

Chemical Physics Letters



Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

York University

Department of Chemistry

Downsview (Toronto)

Ontario M3J-1P3

DTIC  
ELECTE  
NOV 23 1984  
S D E

Reproduction in whole or in part is permitted for any purpose of the United States Government.

This document has been approved for public release and sale; its distribution is unlimited.

84 11 14 009

DTIC FILE COPY

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 33	2. GOVT ACCESSION NO. AD-A147 660	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Correlation of Electronic Charge Transfer Transitions and Electrochemical Potentials. The Bipyrazine(Tetracarbonyl)Molybdenum(0) System in Various Solvents		5. TYPE OF REPORT & PERIOD COVERED Technical Report October, 1983 - October, 1984
7. AUTHOR(s) Elaine S. Dodsworth and A.B.P. Lever*		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Chemistry, York University 4700 Keele St., Downsview, Ontario, M3J 1P3		8. CONTRACT OR GRANT NUMBER(s) N00014-78-C-0592
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research 800 N. Quincy Arlington, VA 22217		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE October, 1984
		13. NUMBER OF PAGES 12
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) This document has been approved for public release and sale; its distribution is unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Prepared for publication in the Journal of Chemical Physics Letters		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) (Metal to ligand) charge transfer, Redox potentials, solvatochromism		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Using a free energy diagram, a relationship is drawn between an optical charge transfer energy and the electrochemical potentials of the donor and acceptor orbitals concerned. The charge transfer spectroscopy and electrochemical potentials of the title complex were studied in various solvents. A linear correlation, with negative slope, was observed between the difference in oxidation and reduction potentials and an MLCT transition. Using some additional solvent data, a number of useful parameters were derived in a fashion which would not be possible through consideration of either technique alone.		

Correlation of Electronic Charge Transfer Transitions and Electrochemical Potentials. The Bipyrazine(Tetracarbonyl)-Molybdenum(0) System in Various Solvents

By Elaine S. Dodsworth and A.B.P. Lever\*

Dept. of Chemistry, York University, Downsview(Toronto), Ontario, Canada, M3J 1P3.

Abstract

Using a free energy diagram, a relationship is drawn between an optical charge transfer energy and the electrochemical potentials of the donor and acceptor orbitals concerned. The charge transfer spectroscopy and electrochemical potentials of the title complex were studied in various solvents. A linear correlation, with negative slope, was observed between the difference in oxidation and reduction potentials and an MLCT transition. Using some additional solvent data, a number of useful parameters were derived in a fashion which would not be possible through consideration of either technique alone.

An electronic charge transfer transition involves excitation from a donor orbital in the ground state of a molecule, to an acceptor orbital in a Franck-Condon (non-equilibrium) excited state of the molecule. In this paper we refer specifically to an MLCT transition, from an orbital,  $\psi_M$ , mainly on the metal, to an orbital,  $\psi_L$ , primarily on the ligand. However the treatment is quite general.

An electrochemical study may, in appropriate cases, define the redox potentials of orbitals related to those above. Thus we may

observe the oxidation potential of  $\psi_M$  in the ground state of the complex  $ML_n$ , and the reduction potential for adding an electron to  $\psi_L$  to form the ground state of the reduced species  $ML_n^-$ .

Previous authors [1-5] have demonstrated qualitative relationships between optical charge transfer energies and electrochemical potentials but now we seek a more quantitative understanding in which quantities not derivable from either electronic spectroscopy or electrochemistry alone, can be obtained by a combined analysis.

In view of the solvation contributions to the parameters obtained with each technique, a combined analysis is best approached within the framework of the collection and comparison of data in a range of solvents. The analysis which follows is based upon theories developed by Born [6], Onsager [7], Kirkwood [8], Lippert [9], Marcus [10] and Meyer [11].

Use of a free energy cycle (Fig.1) permits one to relate the various thermodynamic quantities (as defined in the legend to Fig.1), measurable in the two experimental regimes. Thus the following equalities may be written:-

$$E_{op} = \Delta E_s + \chi_i + \chi_o \quad (1)$$

$$\Delta E_s = \Delta E_g + \Delta(sol) \quad (2)$$

$$\begin{aligned} \Delta E_g &= nF\Delta E(\text{redox}) + \Delta\Delta G_s + Q \\ &= (nF\Delta E'(\text{redox}) + x) + \Delta\Delta G_s + Q \text{ (see text below)} \end{aligned} \quad (3)$$

and hence:-

$$E_{op} = [X_i + nF\Delta E(\text{redox}) + \Delta\Delta G_s + Q] + X_o + \Delta(\text{sol}) \quad (4)$$

where  $X_o + \Delta(\text{sol})$  is the total change in solvation free energy as earlier defined in [10b] eqn.(13), and [9] eqn.B2a, and  $X_i$  and  $X_o$  are the inner sphere (vibrational) and outer-sphere (solvent, but also vibrational in nature) contributions to the reorganisation energy of the transition, respectively. Note that as a consequence of the Franck-Condon nature of the excited state, the transition energy  $E_{op}$  is a free energy in that the entropies of the ground and non-equilibrated excited state are the same [10b].

Equation (4), in which the square bracketed function is solvent independent for a given molecule, provides the important correlation between the two techniques.

The complex  $\text{Mo}(\text{CO})_4\text{bpz}$  (bpz = bipyrazine) [12] displays a strong band, inter alia, attributed to  $d(\text{Mo}(0)) \rightarrow \pi^*(\text{bpz})$  MLCT, whose energy,  $E_{op}$ , varies from about 16,000 to 20,000  $\text{cm}^{-1}$  depending upon the solvent environment and shifting to higher energy with increasing solvent polarity, (Table 1) (cf the solvatochromism of the bipyridine analog [13]). Electrochemical data for a range of solvents are also shown in Table 1.

The reduction potential for the electrochemically reversible  $\text{Mo}(\text{CO})_4\text{bpz}/\text{Mo}(\text{CO})_4\text{bpz}^-$  couple involves addition of an electron to  $\psi_L$  ( $\pi^*$  bpz) forming the radical  $\text{bpz}^-$  bound to  $\text{Mo}(0)$ . This couple shifts to more positive potentials with increasing polarity of the solvent, as the ground state radical anion becomes more solvent

stabilised.

Oxidation occurs at the Mo(0) d manifold but is electrochemically irreversible, due to a following chemical reaction ( $EC_i$  mechanism) [15,16]. However the slow step of the following reaction appears to be Mo-CO bond breaking which is solvent independent. Thus the true thermodynamic potential will be more positive than recorded in Table 1 by a solvent independent quantity, say  $x$  mV (probably  $100 < x < 300$ ). Thus  $\Delta E(\text{redox})$  in (4) is replaced by  $\Delta E'(\text{redox}) + x$ , where  $\Delta E'(\text{redox})$  is the experimental difference between the oxidation and reduction potentials.

A plot of  $E_{op}$  against  $\Delta E'(\text{redox})$  is linear with negative slope (correlation coefficient 0.98):-

$$E_{op} = -1.04 \Delta E'(\text{redox}) + 33,950 \quad (\text{in cm}^{-1})$$

(5)

This is an unexpected result appearing to contradict intuition in that as the potential difference between donor and acceptor orbital decreases, the optical transition energy increases. Such an inverse correlation has not been previously reported. An understanding of this phenomenon develops from further analysis below.

The expression (6) [8] allows one to approximate the solvation free energy of a species as a power series:-

$$\Delta G_s = 0.5 \sum_{n=0}^{\infty} ((n+1)Q_n/b^{2n+1}) [(1-D_s)/((n+1)D_s + n)] \quad (6)$$

where terms higher than  $n = 1$  are ignored and the reader is

referred to the earlier literature [6-11] for detailed discussion of the conditions under which this expression is useful.  $D_s$  is the static dielectric constant of the solvent,  $b$  is the radius of the solute,  $Q_0 = z^2 e^2$ , and  $Q_1 = \vec{\mu}^2$ , where  $\vec{\mu}$  is the dipole moment of the solute species. The term in  $n = 0$  disappears for uncharged species. The difference in solvation free energies of the uncharged and thermally equilibrated ground and excited states,  $\Delta(sol)$ , may be written using (6) as:-

$$\Delta(sol) = \Delta G_s(e) - \Delta G_s(g) = ((\vec{\mu}_e^2 - \vec{\mu}_g^2)/b^3)[(1-D_s)/(2D_s+1)] \quad (7)$$

Following earlier authors [8-11], the Franck-Condon destabilisation of the excited state, due to solvent interactions, may be written:-

$$\chi_0 = ((\vec{\mu}_e - \vec{\mu}_g)^2/b^3)[(1-D_{op})/(2D_{op}+1) - (1-D_s)/(2D_s+1)] \quad (8)$$

where in (7,8) the ground and excited state dipole moments are appropriately discriminated, and  $D_{op}$  is the optical dielectric constant of the solvent (square of the refractive index). The total solvent dependence excluding non-polar contributions (very small [10b]), (eqn.(4)) is  $\Delta E_T = \Delta(sol) + \chi_0$ ; summing (7) and (8) yields (9) (after evaluating the vector products) [9,11]:-

$$\begin{aligned} \Delta E_T = & ((\mu_e^2 + \mu_g^2 - 2\mu_e\mu_g\cos\theta)/b^3)[(1-D_{op})/(2D_{op}+1)] \\ & + 2\mu_g(\mu_e\cos\theta - \mu_g)/b^3[(1-D_s)/(2D_s+1)] \end{aligned} \quad (9)$$

The angle  $\theta$  is that between the ground and excited state

dipoles. The ground state dipole moment lies along the  $C_2$  axis with the negative end pointing towards the CO groups.

Equation (4) can now be recast in the general form:-

$$E_{op} = \chi_1 + \Delta E_g + f(1-D_{op})/(2D_{op}+1) + f'(1-D_g)/(2D_g+1) \quad (10)$$

where  $f$  and  $f'$  group the factors shown in eqn.(9).

In a forthcoming paper [15] we develop this analysis with 23 solvents. Here we shall restrict ourselves to considering six solvents of low polarity and low dielectric constant which might be expected to obey the dielectric continuum model. The optical data thereof (Table 1) obey (10) well according to (in  $\text{cm}^{-1}$ ):-

$$E_{op} = 9500((1-D_{op})/(2D_{op}+1)) - 7600((1-D_g)/(2D_g+1)) + 16,800 \quad (11)$$

with a correlation coefficient of 0.988 and a standard deviation of 65 (the lower set of six solvents shown in Table 1 were used), and where the constant term,  $16,800 \text{ cm}^{-1}$  is associated with  $\chi_1 + \Delta E_g$ . However the data yield a family of solutions which do not differ greatly in their correlation coefficients or standard deviations. Indeed the solution  $f = 0$ ,  $f' = -7110$ , and  $\chi_1 + \Delta E_g = 15,110 \text{ cm}^{-1}$  is not unreasonable (correlation coefficient 0.97, standard deviation 169). This latter solution is, however, inconsistent with the expressions in (9). The solution in (11) is statistically the best, but does not differ significantly from many other solutions in which  $f$  lies between zero and  $9500 \text{ cm}^{-1}$ . However  $f'$  is generally found in the range  $-(7000 - 7700) \text{ cm}^{-1}$  and the constant ranges from about  $15,000 - 17,000 \text{ cm}^{-1}$ . At this stage

of study we note that the approach seems justified but that higher quality and more extensive data are necessary.

The negative value for  $f'$  requires, considering equations (8-11), that, in this system, the dipole moment changes direction by  $180^\circ$  in the excited state relative to the ground state [2,15]. This provides an understanding of the Franck-Condon destabilisation of the excited state by polar solvents, and hence of the negative correlation shown in (5).

For the purpose of indicating how these data may be utilised, we choose a median value of the constant of  $16,000 \text{ cm}^{-1}$ .

Note that in the gas phase,  $\Delta\Delta G_g = 0$ , therefore  $X_1 + nF\Delta E'(\text{redox}) + x + Q = 16,000 \text{ cm}^{-1}$ . Further, use of eqn.(5) provides the value for  $nF\Delta E'(\text{redox})$  in the gas phase by insertion of  $E_{op} = 16,000 \text{ cm}^{-1}$ . Knowing  $\Delta E'(\text{redox})$  allows derivation of  $X_1 + x + Q = -1260 \text{ cm}^{-1}$ . This then leads to the evaluation of  $\Delta\Delta G_g$  (eqn.3). Use of eqn(4) leads to evaluation of  $\Delta(\text{sol}) + X_0$ . These data are also collected in Table 1.

The sum  $(X_1 + x)$  is necessarily positive but  $Q$ , using an appropriate free energy cycle, is estimated to be near  $-0.5V$  [15]. The 'gas phase' optical energy is close to that observed in pentane, as might be anticipated. The procedure provides an interesting set of parameters whose values seems eminently reasonable. Further development on this and related systems should provide the impetus to link the study of electrochemistry and optical spectroscopy and to seek evaluation of other useful parameters, such as the self-exchange energy, which may be derivable from a free energy cycle involving  $Q$ . The merits and boundary conditions inherent in this analysis will be discussed in

more detail in a future publication [15]. We also currently seek emission data which should further define some of the parameters derived.

**Acknowledgments:** The authors are indebted to the Natural Sciences and Engineering Research Council (Ottawa) and the Office of Naval Research (Washington) for financial support. We also gratefully acknowledge useful discussions with Profs. T.J.Meyer and I.M.Walker.

1. P.C.Ford, De F.P.Rudd, R.Gaunders and H.Taube, J.Am.Chem.Soc., 90(1968)1187.
2. J.C.Curtis, B.P.Sullivan and T.J.Meyer, Inorg.Chem., 22(1983)224.
3. A.B.P.Lever, "Inorganic Electronic Spectroscopy", Elsevier Scientific Publ.Co., Amsterdam, 2nd Edition, 1984.
4. A.B.P.Lever, S.Licoccia, P.C.Minor, B.S.Ramaswamy and S.R.Pickens, J.Am.Chem.Soc., 103(1981)6800.
5. S.Goswami, R.Mukherjee and A.Chakravorty, Inorg.Chem., 22(1983)2825.
6. M.Born, Z.Phys., 1(1920)45.
7. L.Onsager, J.Am.Chem.Soc., 58(1936)1486.
8. J.G.Kirkwood, J.Chem.Phys., 2(1934)351.
9. E.Lippert, Z.Elektrochem., 61(1957)962.
10. a) R.A.Marcus, J.Chem.Phys., 39(1963)1734. b) 43(1965)1261.
11. E.M.Kober, B.P.Sullivan and T.J.Meyer, Inorg.Chem., 23(1984)2098.
12. R.J.Crutchley and A.B.P.Lever, Inorg.Chem., 21(1981)2276.

13. H.Saito, J.Fujita and K.Saito, Bull.Chem.Soc.Jpn., 41(1968)863.
14. R.R.Gagne, C.A.Koval and G.C.Lisensky, Inorg.Chem., 19(1980)2854.
15. E.S.Dodsworth and A.B.P.Lever, to be submitted.
16. D.Miholova', L.Pospisil, and A.A.Vlcek, Proc.XXIII Internat.Conf.Coord.Chem., Boulder, CO, USA 1984, and private communication.

Table 1

Electrochemical and Spectroscopic Data<sup>a</sup>

	$E(\text{Mo(I)}/\text{Solvent Mo(0)})^b$	$E(\text{bpz})/\text{bpz}^-$	$\Delta E'(\text{redox})$	$E_{\text{op}}$	$\chi_o + \Delta(\text{sol})$	$\Delta\Delta G_s$
	eV	eV	eV	$\text{cm}^{-1}$	$\text{cm}^{-1}$	$\text{cm}^{-1}$
DMF	0.26	-1.42	1.68	(13,550)	19,650	3650
PC	0.32	-1.41	1.73	(14,000)	19,550	3550
MeCN	0.28	-1.45	1.73	(14,000)	19,450	3450
PY	0.26	-1.52	1.78	(14,350)	18,900	2900
THF	0.30	-1.52	1.82	(14,700)	18,650	2650
DCE	0.34	-1.53	1.87	(15,100)	18,150	2150
DCM			1.90 <sup>c</sup>	(15,350)	17,990	1990
Et <sub>2</sub> O			1.93 <sup>c</sup>	(15,530)	17,790	1790
CHCl <sub>3</sub>			1.98 <sup>c</sup>	(15,950)	17,360	1360
TCM			2.07 <sup>c</sup>	(16,670)	16,610	610
Pent			2.09 <sup>c</sup>	(16,870)	16,400	400
'Gas'			2.14 <sup>c</sup>	(17,260)	16,000	0

a) All electrochemical potentials referenced against ferrocene as internal referant ( $\text{Fc}^+/\text{Fc}$  is at 0.16 eV vs. sce) [14]. Potentials were recorded on Pt electrodes using cyclic voltammetry at scan rates of 100, 50 and 20 mV/s. Confirmatory data were obtained using differential pulse polarography. Data are averages of several experiments. b) The oxidation process is electrochemically irreversible.  $E_p - E_{p/2}$  is comparable to that of the ferrocene couple under the same conditions. Value quoted is  $1/2(E_p + E_{p/2})$ . c) Calculated from eqn.(5) in text. NB  $\Delta E_g + \chi_1 = 16000 \text{ cm}^{-1}$ ,  $\chi_1 + x + Q = -1260 \text{ cm}^{-1}$ .

DMF = dimethylformamide; PC = propylene carbonate; PY = pyridine; THF  
= tetrahydrofuran; DCE = 1,2-dichloroethane; DCM = dichloromethane;  
TCM = tetrachloromethane; Pent = pentane. 'Gas' is extrapolation  
using eqn.(11).

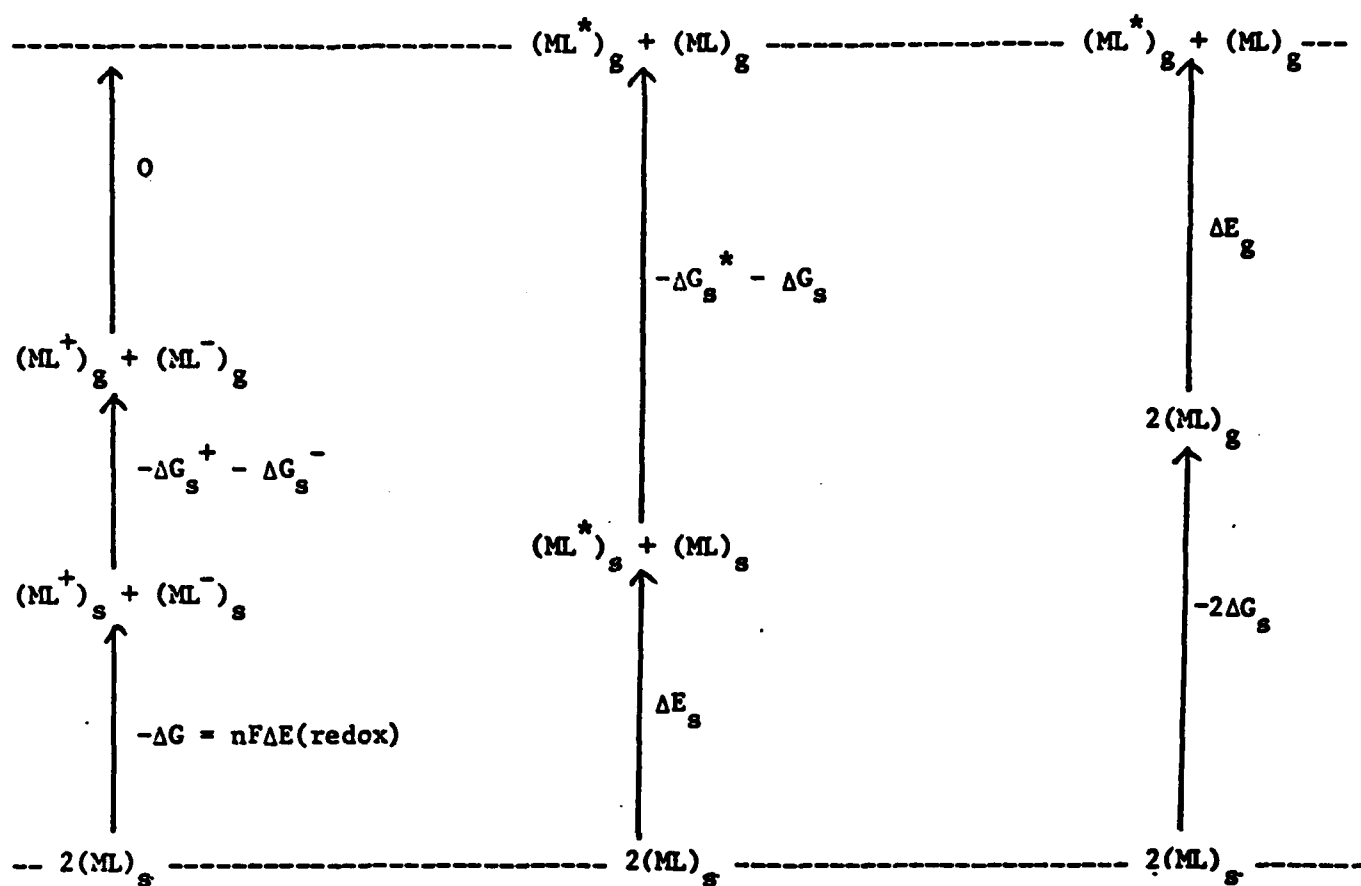


Fig.1 Free energy diagram relating spectroscopic and electrochemical quantities.

$(ML)$  is the neutral species, and  $(ML^*)$ ,  $(ML^+)$  and  $(ML^-)$  are the equilibrated excited, mono-positive and mono-negative species respectively. Similarly  $\Delta G_s$ ,  $\Delta G_s^*$ ,  $\Delta G_s^+$  and  $\Delta G_s^-$  are the solvation free energies for these respective species being defined as the reversible work to transfer these solutes from the gas phase to a solvent.  $\Delta E(\text{redox})$  is defined as the oxidation potential minus the reduction potential of the neutral species.

$\Delta E_g$  is the gas phase excitation energy to the equilibrated excited state.  $\Delta E_s$  is the solvent phase excitation energy to the equilibrated excited state. The quantity  $Q$  is the resonance energy involved in transferring an electron from  $(ML^-)_g$  to  $(ML^+)_g$  yielding  $(ML)_g + (ML^*)_g$ . Note that in the text  $\Delta\Delta G_s = 2\Delta G_s - \Delta G_s^+ - \Delta G_s^-$  and  $\Delta(\text{sol}) = \Delta G_s^* - \Delta G_s$ .

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	<u>No. Copies</u>		<u>No. Copies</u>
Office of Naval Research Attn: Code 413 800 N. Quincy Street Arlington, Virginia 22217	2	Naval Ocean Systems Center Attn: Technical Library San Diego, California 92152	1
ONR Pasadena Detachment Attn: Dr. R. J. Marcus 1030 East Green Street Pasadena, California 91106	1	Naval Weapons Center Attn: Dr. A. B. Amster Chemistry Division China Lake, California 93555	1
Commander, Naval Air Systems Command Attn: Code 310C (H. Rosenwasser) Washington, D.C. 20360	1	Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko Port Hueneme, California 93401	1	Dean William Tolles Naval Postgraduate School Monterey, California 93940	1
Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375	1	U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12	Mr. Vincent Schaper DTNSRDC Code 2830 Annapolis, Maryland 21402	1
DTNSRDC Attn: Dr. G. Bosmajian Applied Chemistry Division Annapolis, Maryland 21401	1	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1	Mr. A. M. Anzalone Administrative Librarian PLASTEC/ARRADCOM Bldg 3401 Dover, New Jersey 07801	1

TECHNICAL REPORT DISTRIBUTION LIST, 359

Dr. Paul Delahay  
Department of Chemistry  
New York University  
New York, New York 10003

Dr. P. J. Hendra  
Department of Chemistry  
University of Southampton  
Southampton SO9 5NH  
United Kingdom

Dr. T. Katan  
Lockheed Missiles and  
Space Co., Inc.  
P.O. Box 504  
Sunnyvale, California 94088

Dr. D. N. Bennion  
Department of Chemical Engineering  
Brigham Young University  
Provo, Utah 84602

Dr. R. A. Marcus  
Department of Chemistry  
California Institute of Technology  
Pasadena, California 91125

Mr. Joseph McCartney  
Code 7121  
Naval Ocean Systems Center  
San Diego, California 92152

Dr. J. J. Auburn  
Bell Laboratories  
Murray Hill, New Jersey 07974

Dr. Joseph Singer, Code 302-1  
NASA-Lewis  
21000 Brookpark Road  
Cleveland, Ohio 44135

Dr. P. P. Schmidt  
Department of Chemistry  
Oakland University  
Rochester, Michigan 48063

Dr. H. Richtol  
Chemistry Department  
Rensselaer Polytechnic Institute  
Troy, New York 12181

Dr. E. Yeager  
Department of Chemistry  
Case Western Reserve University  
Cleveland, Ohio 44106

Dr. C. E. Mueller  
The Electrochemistry Branch  
Naval Surface Weapons Center  
White Oak Laboratory  
Silver Spring, Maryland 20910

Dr. Sam Perone  
Chemistry & Materials  
Science Department  
Lawrence Livermore National Lab.  
Livermore, California 94550

Dr. Royce W. Murray  
Department of Chemistry  
University of North Carolina  
Chapel Hill, North Carolina 27514

Dr. G. Goodman  
Johnson Controls  
5757 North Green Bay Avenue  
Milwaukee, Wisconsin 53201

Dr. B. Brummer  
EIC Incorporated  
111 Chapel Street  
Newton, Massachusetts 02158

Dr. Adam Heller  
Bell Laboratories  
Murray Hill, New Jersey 07974

Electrochimica Corporation  
Attn: Technical Library  
2485 Charleston Road  
Mountain View, California 94040

Library  
Duracell, Inc.  
Burlington, Massachusetts 01803

Dr. A. B. Ellis  
Chemistry Department  
University of Wisconsin  
Madison, Wisconsin 53706

TECHNICAL REPORT DISTRIBUTION LIST, 359

Dr. M. Wrighton  
Chemistry Department  
Massachusetts Institute  
of Technology  
Cambridge, Massachusetts 02139

Dr. B. Stanley Pons  
Department of Chemistry  
University of Utah  
Salt Lake City, Utah 84112

Donald E. Mains  
Naval Weapons Support Center  
Electrochemical Power Sources Division  
Crane, Indiana 47522

S. Ruby  
DOE (STOR)  
M.S. 6B025 Forrestal Bldg.  
Washington, D.C. 20595

Dr. A. J. Bard  
Department of Chemistry  
University of Texas  
Austin, Texas 78712

Dr. Janet Osteryoung  
Department of Chemistry  
State University of New York  
Buffalo, New York 14214

Dr. Donald W. Ernst  
Naval Surface Weapons Center  
Code R-33  
White Oak Laboratory  
Silver Spring, Maryland 20910

Mr. James R. Moden  
Naval Underwater Systems Center  
Code 3632  
Newport, Rhode Island 02840

Dr. Bernard Spielvogel  
U.S. Army Research Office  
P.O. Box 12211  
Research Triangle Park, NC 27709

Dr. William Ayers  
ECD Inc.  
P.O. Box 5357  
North Branch, New Jersey 08876

Dr. M. M. Nicholson  
Electronics Research Center  
Rockwell International  
3370 Miraloma Avenue  
Anaheim, California

Dr. Michael J. Weaver  
Department of Chemistry  
Purdue University  
West Lafayette, Indiana 47907

Dr. R. David Rauh  
EIC Corporation  
111 Chapel Street  
Newton, Massachusetts 02158

Dr. Aaron Wold  
Department of Chemistry  
Brown University  
Providence, Rhode Island 02192

Dr. Martin Fleischmann  
Department of Chemistry  
University of Southampton  
Southampton SO9 5NH ENGLAND

Dr. R. A. Osteryoung  
Department of Chemistry  
State University of New York  
Buffalo, New York 14214

Dr. Denton Elliott  
Air Force Office of Scientific  
Research  
Bolling AFB  
Washington, D.C. 20332

Dr. R. Nowak  
Naval Research Laboratory  
Code 6130  
Washington, D.C. 20375

Dr. D. F. Shriver  
Department of Chemistry  
Northwestern University  
Evanston, Illinois 60201

Dr. Aaron Fletcher  
Naval Weapons Center  
Code 3852  
China Lake, California 93555

TECHNICAL REPORT DISTRIBUTION LIST, 359

Dr. David Aikens  
Chemistry Department  
Rensselaer Polytechnic Institute  
Troy, New York 12181

Dr. A. P. B. Lever  
Chemistry Department  
York University  
Downsview, Ontario M3J1P3

Dr. Stanislaw Szpak  
Naval Ocean Systems Center  
Code 6343, Bayside  
San Diego, California 95152

Dr. Gregory Farrington  
Department of Materials Science  
and Engineering  
University of Pennsylvania  
Philadelphia, Pennsylvania 19104

M. L. Robertson  
Manager, Electrochemical  
and Power Sources Division  
Naval Weapons Support Center  
Crane, Indiana 47522

Dr. T. Marks  
Department of Chemistry  
Northwestern University  
Evanston, Illinois 60201

Dr. Micha Tomkiewicz  
Department of Physics  
Brooklyn College  
Brooklyn, New York 11210

Dr. Lesser Blum  
Department of Physics  
University of Puerto Rico  
Rio Piedras, Puerto Rico 00931

Dr. Joseph Gordon, II  
IBM Corporation  
K33/281  
5600 Cottle Road  
San Jose, California 95193

Dr. D. H. Whitmore  
Department of Materials Science  
Northwestern University  
Evanston, Illinois 60201

Dr. Alan Bewick  
Department of Chemistry  
The University of Southampton  
Southampton, SO9 5NH ENGLAND

Dr. E. Anderson  
NAVSEA-56233 NC #4  
2541 Jefferson Davis Highway  
Arlington, Virginia 20362

Dr. Bruce Dunn  
Department of Engineering &  
Applied Science  
University of California  
Los Angeles, California 90024

Dr. Elton Cairns  
Energy & Environment Division  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, California 94720

Dr. D. Cipris  
Allied Corporation  
P.O. Box 3000R  
Morristown, New Jersey 07960

Dr. M. Philpott  
IBM Corporation  
5600 Cottle Road  
San Jose, California 95193

Dr. Donald Sandstrom  
Department of Physics  
Washington State University  
Pullman, Washington 99164

Dr. Carl Kannewurf  
Department of Electrical Engineering  
and Computer Science  
Northwestern University  
Evanston, Illinois 60201

TECHNICAL REPORT DISTRIBUTION LIST, 359

Dr. Robert Somoano  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California 91103

Dr. Johann A. Joebstl  
USA Mobility Equipment R&D Command  
ORDME-EC  
Fort Belvoir, Virginia 22060

Dr. Judith H. Ambrus  
NASA Headquarters  
M.S. RTS-6  
Washington, D.C. 20546

Dr. Albert R. Landgrebe  
U.S. Department of Energy  
M.S. 68025 Forrestal Building  
Washington, D.C. 20595

Dr. J. J. Brophy  
Department of Physics  
University of Utah  
Salt Lake City, Utah 84112

Dr. Charles Martin  
Department of Chemistry  
Texas A&M University  
College Station, Texas 77843

Dr. H. Tachikawa  
Department of Chemistry  
Jackson State University  
Jackson, Mississippi 39217

Dr. Theodore Beck  
Electrochemical Technology Corp.  
3935 Leary Way N.W.  
Seattle, Washington 98107

Dr. Farrell Lytle  
Boeing Engineering and  
Construction Engineers  
P.O. Box 3707  
Seattle, Washington 98124

Dr. Robert Gotscholl  
U.S. Department of Energy  
MS G-226  
Washington, D.C. 20545

Dr. Edward Fletcher  
Department of Mechanical Engineering  
University of Minnesota  
Minneapolis, Minnesota 55455

Dr. John Fontanella  
Department of Physics  
U.S. Naval Academy  
Annapolis, Maryland 21402

Dr. Martha Greenblatt  
Department of Chemistry  
Rutgers University  
New Brunswick, New Jersey 08903

Dr. John Wasson  
Syntheco, Inc.  
Rte 6 - Industrial Pike Road  
Gastonia, North Carolina 28052

Dr. Walter Roth  
Department of Physics  
State University of New York  
Albany, New York 12222

Dr. Anthony Sammells  
Eltron Research Inc.  
710 E. Ogden Avenue #108  
Naperville, Illinois 60540

Dr. W. M. Risen  
Department of Chemistry  
Brown University  
Providence, Rhode Island 02192

Dr. C. A. Angell  
Department of Chemistry  
Purdue University  
West Lafayette, Indiana 47907

Dr. Thomas Davis  
Polymer Science and Standards  
Division  
National Bureau of Standards  
Washington, D.C. 20234